GENSETS Program Overview

B. PROGRAM OVERVIEW

1. SUMMARY

The GENSETS Program – ***GEN**erators for **S**mall **E**lectrical and **T**hermal **S**ystems* – seeks to fund the development of potentially disruptive generator technologies that will enable widespread deployment of residential Combined Heat and Power (CHP) systems. Here, CHP is defined as the distributed generation of electricity from piped-in natural gas fuel at a residence or a commercial site complemented by use of exhaust heat for local heating and cooling. If adopted widely by U.S. residential and commercial sectors, GENSETS CHP systems could lead to annual primary energy *savings* of more than 5 quadrillion BTU (quads). GENSETS systems could also provide annual CO_2 emissions *reductions* of more than 200 million metric tons, which is roughly 10% of the CO_2 produced annually from U.S. electricity generation and 4% of total U.S. annual CO_2 emissions.

The GENSETS Program seeks transformative generators/engines with 1 kW of electrical output (kW_e) that have high efficiency (40% fuel to electricity), long life (10 years), low cost ($3,000 per system), and low emissions. Heat engines and generators capable of achieving these targets may include internal and external combustion engines, turbines, and solid state devices such as thermophotovoltaics, thermionic emitters, and thermoelectrics. It is anticipated that the same technologies developed for 1-kW_e engines in GENSETS could be adapted to build larger engines with even higher efficiencies for various commercial sectors of the U.S.

2. BACKGROUND AND MOTIVATION

2.1 Opportunity and Impact of CHP

In 2013, U.S. central-station power plants consumed 38.2 quads of primary energy to generate 12.4 quads of electricity with an average electricity generation efficiency of 33% when aggregated over all primary energy sources, including coal, natural gas, nuclear, hydro, and wind[1]. In the process, 67% of the primary energy was wasted as heat (25.8 quads) and about 2 billion metric tons of CO_2 were emitted to the environment, which is about 38% of the total annual U.S. CO_2 emissions[2]. Distributed CHP systems are an alternative to central-station power plants. In these systems, an electrical generation system located in a residence or at a commercial site consumes natural gas to generate electricity locally and then the exhaust heat is utilized for local heating needs (in contrast to being wasted at central-stations). The combined efficiency of primary energy usage in CHP can be higher than 80%. Since about 75% of the electricity generated from all central-station power plants is consumed by the residential and commercial sectors, CHP in these sectors can have a huge impact on both energy savings and CO_2 emissions reduction. In addition, CHP can bring power resilience to households and commercial entities to counter weather-related outages that cause billions of dollars of losses to the U.S. economy annually.[3]

The current best-performing engines for CHP at small-scale (<2-kW_e) have a fuel-to-electricity efficiency of about 26% and a Capital Expenditure (CAPEX) of more than $6,000 per kW_e. The combination of low efficiency and high cost has significantly limited CHP deployment in the U.S. residential sector, resulting in fewer than 1,000 total installed units[4], or a deployment rate of less than 0.002%. In order to fundamentally change this dynamic, ARPA-E believes that an efficiency of at least 40% and a system cost of less than $3,000 per kW_e is needed. The ARPA-E GENSETS program seeks new engine (generator) technologies to enable widespread deployment of CHP, primarily for the residential sector. However, if successful, it is anticipated that the same technologies could be readily scaled up to enable extensive CHP implementation in the commercial sector. Roughly 70 million U.S. residential homes[2] currently have access to natural gas,

[1] https://flowcharts.llnl.gov/content/energy/energy_archive/energy_flow_2013/2013USEnergy.png
[2] www.eia.gov
[3] Arghandeh et al. IEEE Power & Energy Magazine, September/October, 2014, p. 76.
[4] http://arpa-e.energy.gov/sites/default/files/Mike%20Cocking_Marathon.pdf

critical for widespread CHP deployment. To enable residential CHP adoption, ARPA-E believes that inexpensive, efficient, small-scale generators are the key enabler.

2.2 The Optimal CHP System

Optimal Size and Efficiency

A single size engine/generator will not satisfy every application in a diverse residential CHP market. However, ARPA-E's analysis, presented below, indicates that a 1-kW_e output is optimal for most residential applications.

In order to define an optimal engine/generator size that could be deployed across the entire U.S. residential sector, ARPA-E analyzed the energy consumption profile using the National Renewable Energy Laboratory (NREL) BEopt tool[5] for twelve representative cities in the seven Building America Climate Regions[6]. For example, Figure 2 shows the hourly energy consumption/load profile for Chicago (in the cold climate zone) during representative summer and winter days. The green solid line represents the output from a theoretical 1-kW_e generator running at a steady-state all day. In both the January and July cases, a 1-kW_e system would send a small amount of electricity to the grid during the early morning hours and the household would extract electricity from the grid during evening hours to supplement their electricity needs. For most days, the electricity from the 1-kW_e system is slightly below the household needs and hence the household would need to extract a small amount of electricity from the grid.

A 1-kW_e 40% electrical efficiency system would generate 1.5 kW per hour of exhaust heat, represented by the light-blue areas enveloped by thin dashed red lines in Figure 2. For Chicago, the exhaust heat would be able to satisfy all the domestic hot water needs and also contribute to space heating requirements during the cold-weather months. Additional space heating could be provided by a natural gas fired furnace, which is likely >80% efficient. In the summer months, the exhaust heat produced from the CHP system is beyond the domestic hot water requirements. However, air conditioning energy saving opportunities could be realized through use of advanced adsorption chillers.

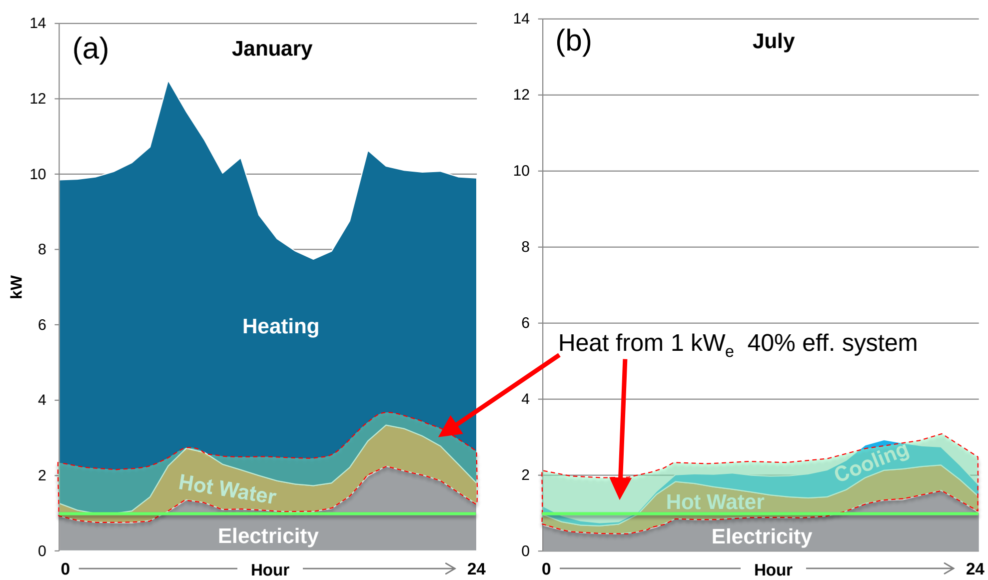

Figure 2. Hourly residential energy consumption profile for Chicago during (a) January and (b) July. The turquoise-colored areas enveloped by the red dashed lines represent the heat output from a 1-kW_e system at 40% electrical efficiency.

Larger CHP systems are unnecessary for ordinary homes in the residential sector and would lead to reduced overall efficiency. First, excess electricity generated by a larger system would need to be delivered to the grid, which may or may not pay retail or even wholesale electricity price depending on the local and the electricity utility policies. Second, systems above 1 kW_e would produce a significant amount of unused exhaust heat during the warm-weather months. This would

[5] https://beopt.nrel.gov/
[6] http://www.eia.gov/consumption/residential/maps.cfm

necessitate the system to operate at a reduced load (which lowers the efficiency) or to operate only in cold weather months (which reduces the capacity factor). Similar conclusions are drawn from ARPA-E's examination of load data for the 11 other cities located across different climate zones[7]. Based on this analysis, ARPA-E has determined that 1-kW_e is an appropriate scale in terms of electrical and thermal output for application across the U.S. and focuses this FOA on developing a generator to provide that output with 40% electrical efficiency.

Minimum System Lifetime and Maximum Viable CAPEX

Reducing total cost of ownership will be a key enabler to CHP system adoption. This FOA focuses primarily on the CAPEX associated with the gas to electrical generation part of the system. The CAPEX defined here includes the system cost but excludes the installation and balance of plant costs. (The balance of plant includes a smart meter and heat exchangers to dissipate excess heat not being used).

ARPA-E performed a techno-economic analysis for a hypothetical residence with an hourly 1 kW electric and 1.5 kW thermal load (both assumed constant for simplicity). The 2013 national average retail price of electricity ($0.11 per kWh) and natural gas ($10.85 per thousand cubic feet) were used in the analysis. In this case, a customer would pay about $1,700 a year to obtain electricity from the grid and natural gas through a pipeline, which serves as the baseline scenario. Replacing this with CHP would require the homeowner to pay the initial labor costs at installation and balance of system costs of ~$1,400, and an Operation and Maintenance (O&M) cost of roughly $0.005 per kWh. ARPA-E analysis shows breakeven for the homeowner in 7 years if the 40%-efficient generator system costs about $3,000 in CAPEX. The homeowner would pay about $1,240 per year, and would be able to use savings in electricity and natural gas costs to recover the cost of the CHP system and pay ongoing O&M costs.

More analysis was performed by varying the values of CAPEX, lifetime/durability of the system, electricity price, and capacity factor. The results clearly show that even with 40% electrical efficiency, if the system lifetime is below 10 years, it is very hard to compete with today's baseline. A lower CAPEX of $1,000 would provide a payback period of three years, but ARPA-E recognizes that it is unlikely that a 40%-efficient generator could be produced at such low cost.

ARPA-E recognizes that installing and maintaining the electricity grid requires high fixed-cost investment in wires, transformers, etc. Currently, residential customers pay for these costs predominantly through their $/kWh retail electricity rates. As the penetration of distributed generation continues to grow, traditional utility rate structures that recover fixed costs through variable rates can cause problems such as utility revenue inadequacy and cross-subsidization between customers. Projecting the actual cost of grid electricity into a future with widespread CHP penetration is highly uncertain, since customers who install CHP systems would continue to rely on a connection from the electrical grid and they will continue to pay a portion of the cost of grid installation and maintenance. A lower bound for comparison would be to use the current wholesale electricity price in the analysis ($0.06 to $0.10 per kWh), which with a 7-year payback indicates that the CAPEX would likely need to be below $2,000 for the 40% generator.

In light of the considerations above, the GENSETS FOA sets a CAPEX target of $3,000 and a system lifetime of 10 years. These targets provide a fair balance between payback time for the consumer in light of uncertainty in future electricity prices associated with high CHP penetration.

Emissions and Noise Requirements

In order to be widely deployable across the country over time, ARPA-E expects CHP systems to meet the 2007 California Air Resources Board (CARB) emissions regulations for natural gas powered electrical generation technologies in distributed generation applications[8]. The GENSETS targets for emission of nitrogen oxide (NOx), carbon monoxide (CO) and volatile organic compounds (VOCs) are 0.07, 0.10, and 0.02 lb/MW-hr, respectively.

The GENSETS Program also utilized the Environmental Protection Agency (EPA) New Source Performance Standards (NSPS) on Particulate Matter (PM) to set the limit at 0.4 g/kW-hr[9]. The GENSETS Program also aims at regulating both CO_2 and CH_4 greenhouse gas (GHG) emissions using a CO_2 equivalent (CO_2eq) number that is calculated based on the 100 year global warming potential (GWP) value of 28 [10] for CH_4; and the system-out CO_2eq limit is 1100 CO_2eq lb/MW-hr.

[7] http://arpa-e.energy.gov/sites/default/files/JC%20Zhao_Small%20engines%20for%20CHP%20workshop%20Introduction_final.pdf
[8] 17 CCR §94203(b) (California Code of Regulations)
[9] 40 C.F.R. § 1039.101
[10] http://www.ipcc.ch/report/ar5/wg1/

The acceptable target noise level for customers, who likely would install the CHP systems in their basement, is 55 dB (A-weighting) measured at a 3-foot distance.

2.3 Technical Opportunities, Challenges and State-of-the-Art

Various systems have been commercialized or are in development for CHP applications requiring <5-kW_e, including internal combustion engines (ICEs), external combustion engines such as Stirling engines and Rankine engines, fuel-cells, micro-turbines, and solid state devices such as thermionic generators, thermoelectrics, and thermophotovoltaics (TPV)[11].

Table 1 shows best-in-class electrical conversion efficiencies for small-scale CHP applications[12,13,14]. The heat recovery efficiency is for domestic heating and hot-water. The total CHP efficiency is the sum of the electrical conversion and heat recovery efficiencies.

For a combustion engine, the final electrical efficiency η_e can be written as:

$$\eta_e = \eta_{comb} \cdot \eta_{ind} \cdot \eta_m \cdot \eta_{alt} \qquad \text{(Eq. 1)}$$

The combustion efficiency η_{comb} represents the portion of the fuel's energy that is converted into useful heat. The indicated cycle efficiency η_{ind} refers to the fraction of the useful heat energy that is converted into closed-cycle work after losses. The mechanical efficiency η_m is the percent of useful closed cycle work that is available at the shaft taking into account friction and parasitic losses. Finally, the alternator efficiency η_{alt} represents the portion of shaft work that is converted into useful electrical power. To reach the 40% η_e target, improvements in the contributing efficiencies in Eq. (1) are sought.

Table 1: State-of-the-art efficiencies of engines for small-scale CHP applications[12,13,14]

Device/Parameter	ICE	Stirling engine	Micro-turbine	Thermophotovoltaic
Electrical power (kW_e)	1.0	2.0	3.0	1.5
Thermal power (kW)	2.5	8.0	15.0	9.4
Fuel Power (kW)	3.8	10.0	18.8	12.2
Electrical conv. eff. (%)	26.3	20.0	16.0	12.3
Heat recovery eff. (%)	65.7	80.0	80.0	79.8

ARPA-E recognizes there is a significant technology gap between the current state-of-the-art engine fuel to electricity efficiency (~26%) and the 40% target, especially while meeting demands on CAPEX/cost ($3,000) and system lifetime/durability (10 years). A fundamental challenge in devising small-scale heat engines with high efficiency is minimizing heat losses. With the exception of incomplete combustion, the main losses suffered when converting one form of energy to another are attributable to heat transfer losses. The challenge is significant for 1 kW_e engines where the high surface area to volume ratio leads to increased heat transfer loss. Figure 3 shows a typical small-scale mechanical heat engine efficiency loss breakdown. This figure suggests many methods that will likely be needed to increase the engine efficiency: 1) effective recuperation of the exhaust heat using bottoming cycles; 2) reduced heat transfer through the engine wall using thermal barriers or reduced combustion temperature to reduce the gradient across the wall; 3) effective recuperation of heat transferred to the engine coolant; and 4) reduced frictional loss through better lubrication and other techniques. Additional efficiency gains could also be obtained by reducing the parasitic losses in converters and electronics. Finally, coupling a mechanical engine with a solid state device such as a thermoelectric generator may be necessary to achieve 40% electrical efficiency. Therefore, successful systems may require topping or bottoming cycles as well as potential use of emissions reduction sub-systems. Innovative approaches together with cost-effective manufacturing technologies are needed to achieve the CAPEX target.

[11] http://www.microchap.info/micro_chp_products.htm
[12] Barbieri et al., Applied Energy, V.97, 2012, pp.723-733
[13] De Paepe et al., Energy Conversion and Management, V.47, 2006, pp. 3435-3446
[14] http://world.honda.com/news/2011/p110523Gas-Engine-Cogeneration/

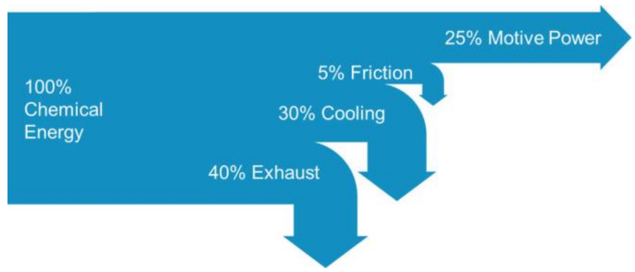

Figure 3. Typical small-scale heat engine efficiency losses.

The subsequent technical examples are meant only to illustrate principles; they are not meant to prescribe or limit the technical approaches that might receive an award through the GENSETS Program. ARPA-E will consider making an award to any application that effectively addresses the technical challenges and leads to the development of technology that can meet or exceed the associated Technical Performance Targets specified in Section I.E. ARPA-E will make awards only to transformational solutions that go well beyond the state-of-the-art.

Internal Combustion Engines (ICEs)

For generations, ICEs have been the predominant engine for a range of applications and have also penetrated the CHP market. However, ICE efficiencies remain far below the target of this FOA. Nonetheless, there are many potential opportunities for increasing efficiency. For example, the natural gas powered ICE, noted in the second column in Table 1, achieves high efficiency by employing an over-expanded Atkinson cycle and a unique geometric design.[14]

Novel strategies for reducing in-cylinder heat transfer[15] and friction[16] and/or novel methodologies for tapping coolant and exhaust heat need to be devised for ICEs to deliver 40% electrical efficiency at the 1-kW_e size. New understanding of combustion science such as boosted homogeneous charge compression ignition (HCCI) [17] and novel implementation of more effective thermodynamic cycles such as Miller cycle and Humphrey cycle may also enable significantly higher efficiencies. Some of the current technologies in this direction are Miller cycle using variable valve timing (VVT) [18], boosted HCCI, advanced Corona ignition system (ACIS) [19], lean natural gas combustion[20], low temperature combustion using high exhaust gas recirculation (EGR) [20], opposed two-stroke piston engine[21], free piston linear generator [22,23,24], and employment of five-stroke cycle[25]. It should be noted that above examples do not entail ARPA-E's endorsement of a specific technology but they are listed here to stimulate more ideas/concepts for efficiency enhancements.

Benchmarking experiments by Thomas[26] show that, with a three-way catalyst, a 4.7 kW_e ICE CHP system with a fuel to electricity conversion efficiency of 24.7% produces about 0.1 mg/Nm^3 of CO and 8.4 mg/Nm^3 of NOx emissions. Boosted HCCI or lean natural gas combustion can increase the electrical efficiency, but that may lead to higher CO and hydrocarbon (HC) emissions as well as higher combustion noise due to increased rates of in-cylinder peak pressure rise. Mitigation of HC and CO emissions can potentially be achieved by using a high-efficiency oxidation catalyst or a catalytic afterburner. HCCI and lean combustion can reduce system-out NOx, and additional NOx reduction can be achieved with the use of EGR, lean NOx trap (LNT), or selective catalytic reduction (SCR) to meet the emissions standards of the FOA. While the emissions challenge can be overcome, the cost of mitigation needs to be minimized to meet GENSETS targets.

[15] Chan and Kohr, Journal of Materials Engineering and Performance, V.9, 2000, pp.103-109
[16] http://energy.gov/sites/prod/files/2014/03/f8/deer12_gangopadhyay.pdf
[17] Kobayashi et al., Journal of Natural Gas Science and Engineering, V.3, 2011, pp.651-656
[18] Fontana and Galloni, Applied Energy, V.86, 2009, pp.96-105
[19] Burrows, J., et al., MTZ, V.74, No. 6, 2013, pp.38-41
[20] Caton, J.A., Energy Conversion and Management, V.79, 2014, pp.146-160
[21] http://www.achatespower.com/pdf/light-duty_engine_study.pdf
[22] Kosaka, H., Akita, T., Moriya, K., Goto, S. et al. (2014) SAE Technical Paper 2014-01-1203 doi: 10.4271/2014-01-1203
[23] Goto, S., Moriya, K., Kosaka, H., Akita, T. et al. (2014) SAE Technical Paper 2014-01-1193 doi: 10.4271/2014-01-1193
[24] Van Blarigan et al. SANDIA Report SAND99-8206, 1998
[25] Kéromnès et al., Energy Conversion and Management, V.82, 2014, pp.259-267
[26] Thomas, B., Applied Thermal Engineering, V.28, 2008, pp.2049-2054

Stirling Engines

Although Stirling engines may be the most mature external combustion engines that have penetrated the CHP market, considerable innovation would be needed to meet the targets of this FOA. As shown in Table 1, the current state-of-the-art small-scale Stirling engines have roughly 20% electrical efficiency.

Realizing 40% electrical efficiency will likely require significant improvements in combustion efficiency and indicated efficiency by lowering the heat losses. Significant improvements in mechanical efficiency will also be needed to achieve the FOA target. Much higher efficiency may be achieved by: 1) increasing the maximum working fluid temperature to 1000 °C or even 1100 °C using state-of-the-art high-temperature alloys[27,28] and additive manufacturing technology[29] – leading to much higher thermodynamic cycle Carnot efficiencies, 2) augmenting the recuperation effectiveness, and 3) reducing the parasitic losses in converters and electronics. ARPA-E strongly encourages innovative concepts that couple a combustion engine such a Stirling engine with a solid state device such as a thermoelectric generator and/or a thermionic emitter to achieve 40% electrical efficiency.

Thomas[26] also shows that a 9 kW_e Stirling engine CHP system with a fuel to electricity conversion efficiency of 26.8% produced about 191 mg/Nm^3 of CO and 105 mg/Nm^3 of NOx emissions. The system incorporated a flameless oxidation burner[30] and a catalyst for emissions reduction. When higher combustion temperatures are to be used to achieve higher Carnot efficiency, both HC and CO emissions can be reduced but the NOx emissions would increase and may require further exhaust after-treatment such as EGR, combustion gas recirculation (CGR)[31], SCR, or LNT.

Micro-Turbines

Micro-turbines are essentially low-powered versions of gas-turbines used in Brayton cycle power plants. Micro-turbine technologies are more mature for applications over 20 kW_e than for the 1-kW_e regime. For applications less than 5 kW_e there are no major commercial products available; however, a prototype 3 kW_e (15 kW thermal output) system for small-scale CHP achieving 16% electrical efficiency and 80% thermal efficiency has been reported and is being commercialized.[32] A rig testing by Visser et al.[33] of another 3 kW_e micro-turbine system shows that much of the fuel energy goes into exhaust (47%), and heat, friction and parasitic losses (39.4%). Higher efficiency micro-turbines may be developed by reducing viscous losses (loss due to low Reynold’s number flow) in the turbine passages, lower heat losses (loss due to high surface-to-volume ratios), and lower mechanical and parasitic losses. A suite of technologies may be required to achieve this FOA’s targets such as new turbine design concepts, high efficiency intake-air recuperation, reduced heat and frictional losses, use of newer materials such as SiC and Si_3N_4 [34,35] to increase the material temperature limit to 1200 °C or higher for enabling higher thermodynamic cycle Carnot efficiencies[36], and incorporation of solid state devices and other topping or bottoming cycles such as organic Rankine cycle[37].

Only large-capacity turbines have demonstrated CARB 2007 distributed generation emissions compliance[38]. Micro-turbines may produce higher HC and CO due to inefficient combustion. Higher combustion/gas temperatures will be needed to increase the fuel to electrical conversion efficiency, which will likely result in higher NOx emissions and thus require further exhaust after-treatment such as EGR, SCR, or LNT. Mitigation of HC and CO can potentially be achieved by using a high-efficiency oxidation catalyst or a catalytic afterburner. Other low NOx technologies could include the flameless oxidation burner or ultra-low NOx burner[39].

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[27] Harada, H. Proceedings of the International Gas Turbine Congress 2003 Tokyo, IGTC2003Tokyo KS-2, pp. 1-9.
[28] Pollock, T; Tin, S. J. Prop Power, vol. 22, 2006, pp. 361-374.
[29] Gibson, et al. Additive Manufacturing Technologies, Springer, 2010.
[30] Wünning, J.G.,Thermprocess Symposium, Düsseldorf, 2003 (http://www.flox.com/documents/03_TP.pdf)
[31] http://www.sgc.se/ckfinder/userfiles/files/SGC144.pdf
[32] http://www.mtt-eu.com/applications/micro-chp
[33] Visser et al., ASME Journal of Engineering for Gas Turbines and Power, V.133, 2011, pp.042301-1-042301-8
[34] http://infohouse.p2ric.org/ref/20/19293.pdf.
[35] Singh, M. et al. DOI: 10.1002/9781118144091.ch26 (2011).
[36] McDonald and Rogers, Applied Thermal Engineering, V.28, 2008, pp.60-74
[37] Mago and Luck, Applied Energy, V.102, 2013, pp.1324-1333
[38] http://www.arb.ca.gov/energy/dg/eo/dg018.pdf
[39] http://www.energy.ca.gov/2013publications/CEC-500-2013-043/CEC-500-2013-043.pdf

Solid-State Devices

Several solid-state devices are applicable to power generation and CHP systems, and could be used as topping or bottoming cycles on combustion/mechanical engines. Most prominent among these are thermoelectric generators, thermionic emitters, Na/H/O ion expansion electrochemical devices, thermophotovoltaics (TPVs), and pyroelectrics. There are only a handful of demonstrated technologies in engineered systems. Data on one particular TPV system indicates an electrical efficiency of 12.3% for a 1.5 kW_e system with component efficiency of over 15% [40] as shown in Table 1. Current state-of-the-art efficiencies of solid state devices have not exceeded 20%, however they possess significant potential for achieving higher efficiencies with newer materials, architectures, and manufacturing processes[41,42,43]. As mentioned before, they can also play a significant role in reaching high overall system efficiency by serving as either a topping or a bottoming cycle to another device/engine.

The emissions and noise challenges for solid state devices are essentially the same as the Stirling engines where natural gas combustion is used to generate heat to be converted to electricity in these devices.

C. PROGRAM OBJECTIVES

As seen in Section I.B of this FOA, all the current state-of-the-art engines for CHP suffer from low efficiency and high cost. The ARPA-E GENSETS program is seeking fundamentally disruptive technologies that can markedly improve the fuel to electricity efficiency to 40% while delivering 1 kW_e electrical power at low cost. The total system cost should not exceed $3,000 at high volume (e.g., 1 million unit scale) (excluding $1,400 installation and balance of plant costs). These technologies must meet the emissions requirements documented in detail in Section I.E of this FOA. The key program objectives are outlined below in detail:

Achieve 40% fuel-to-electrical power generation efficiency

The goal of the ARPA-E GENSETS program is to leverage existing technologies and encourage disruptive concepts that can realize the 40% electrical efficiency target and deliver low cost 1 kW_e systems for residential CHP applications.

Comply with emissions standards

As described above, widespread deployment of CHP systems would result in significant reduction in CO_2 emissions as compared to central-station power plants. However, significant challenges exist in reducing CO, NOx and VOCs in natural gas powered CHP systems at the 1 kW_e size. Through the GENSETS FOA, ARPA-E is expecting generator concepts with high combustion efficiencies that produce emissions that comply with both the 2007 CARB emissions regulations on NOx, CO and VOCs and the EPA NSPS limit on PM. A system-out GHG limit is set at 1100 CO_2eq lb/MW-hr to ensure compliance with prevailing state-level environmental standards.

Achieve long lifetime/durability

The target for the total system life is 10 years with a capacity factor of 99.9%, i.e., the system should have the capability of running continuously between services (e.g., oil change or cathode replacement) which should not be more than once a year, corresponding to about 8,000 running hours between service intervals. Based upon reported performance, this is a realistic goal to achieve for ICEs and Stirling engines. For example, for a 1 kW_e CHP system,[14] a manufacturer reports 6,000 running hours or 3 years between service, which is close to the target set by this FOA. Also, a Stirling engine manufacturer has demonstrated maintenance-free operation for 100,000 hours (11 years) and eight other engines have more than 8,000 hours and are still running. The system lifetime target will be a challenge for new device types that are still rapidly-evolving in design such as solid state devices and micro-turbines. Accelerated testing should be used by GENSETS performers to project actual field lifetimes from shorter duration test data.

[40] http://www.jxcrystals.com/old_TPV/RomeCHP.pdf
[41] http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/19252/1/98-0546.pdf
[42] Caillat et al., Nuclear and Emerging Technologies for Space, 2012 (http://www.lpi.usra.edu/meetings/nets2012/pdf/3077.pdf)
[43] Lee et al., Applied Thermal Engineering, V.37, 2012, pp.30-37

Reduce system cost to enable widespread penetration of residential CHP

The total CAPEX here includes the system cost but excludes the installation and balance of plant costs. The CAPEX target for the 1 kW_e system is no more than $3,000.

D. TECHNICAL CATEGORIES OF INTEREST

The ARPA-E GENSETS program will fund transformational technologies that can create a paradigm shift in the residential heat and power generation process. ARPA-E expects GENSETS to open pathways for high-efficiency, low-emissions, long-life, cost-effective, 1-kW_e generators that can enable significant energy savings and CO_2 emissions reduction.

Applicants must present a well-justified, realistic proposal for the design, construction, and demonstration of a complete engine/generator system that meets all the technical performance targets. Specifically, the systems should accept natural gas at standard residential delivery pressures as their only fuel input and produce 60 Hz ac electrical output at 110 V.[44]

Example technologies of interest, either as standalone solutions or in combinations, include, but are not limited to:

- Internal combustion engines
- External combustion engines such as Stirling engines and steam engines
- Any other novel engines (e.g. detonation engines, thermoacoustic engines, free-piston engines, rotary engines etc.)
- Combustion turbines such as micro-turbines
- Micro Rankine cycles

Novel concepts that incorporate exhaust and coolant waste-heat recovery,

- Novel concepts to improve combustion efficiency and emissions reduction such as exhaust gas recirculation (EGR) or flue gas recirculation (FGR), homogeneous charge compression ignition (HCCI), spark-assisted HCCI (SA-HCCI), corona ignition, and laser ignition
- Thermophotovoltaics
- Thermionic emitters
- Thermoelectric generators
- Pyroelectrics
- Ion expansion electrochemical devices for electricity generation
- Innovative integration of topping cycles and/or bottoming cycles
- Combinations of the above devices and concepts

E. TECHNICAL PERFORMANCE TARGETS

Only technologies with potential to meet or exceed all GENSETS primary targets will be considered for funding. Program teams must propose to meet the following primary targets and will need to demonstrate these targets by the end of the award period.

Number	Property	Primary Target
1.1	Electric power generation capacity	1 kW_e
1.2	Fuel to electricity conversion efficiency	≥40%
1.3	Useful heat energy output (> 80°C)	>1 kW/kW_e
1.4	Capacity factor	≥99.9%
1.5	Complete system up front cost (not including	≤$3000/$kW_e$

[44] The proposed systems are not required to meet all grid interconnection requirements. However, applicants should explain in the full proposal how low power quality output can be made compatible with grid requirements.

	balance of plant and installation)	
1.6	Lifetime	≥10 years
1.7	Total system-out NOx	≤0.07 lb/MW-hr
1.8	Total system-out CO	≤0.10 lb/MW-hr
1.9	Total system-out VOC	≤0.02 lb/MW-hr
1.10	Total system-out CO_2eq (CO_2 + CH_4 only)	≤1100 lb/MW-hr
1.11	Particulate matter (PM)	≤0.4 g/kW-hr
1.12	System noise	≤55 dB(A) (3-feet away)

In addition, technologies should propose to meet the following secondary targets:

Number	Property	Secondary Target
1.13	Methane number for operation	≥70
1.14	Number of regular maintenance services	≤1/year
1.15	Operation and maintenance cost	≤ $0.005/kWh
1.16	Time for regular maintenance	≤ 60 minutes/service
1.17	System mass	≤ 150 kg

Supplementary Explanations of Targets

1.1 The system concept should target 1-kW$_e$ generation. However, if the efficiency target is demonstrated in a device which has < 1-kW$_e$ power producing capacity, then a detailed scaling analysis should be presented to project efficiency at 1-kW$_e$. Systems larger than 1-kW$_e$ are not of interest.

1.2 Natural gas fuel to ac electricity conversion efficiency is based on lower heating value (LHV) of pipeline natural gas with 983 Btu per cubic foot. Individual component efficiencies of 40% are not sufficient. A device delivering 40% electrical efficiency relative to its input heat energy is not acceptable. Solid-state devices should be treated as external combustion engines and electrical efficiency should be described as in Eq. 1 ($\eta_e = \eta_{comb} \cdot \eta_{ind} \cdot \eta_m \cdot \eta_{alt}$).

1.3 Residential hot-water and space heating output provided by CHP system should be > 1 kW/kW$_e$ at > 80 °C.

1.4 The system is expected to run continuously between the scheduled regular maintenance and restart easily. 1.5

1.5 The engine/generator system, including emissions mitigation and dissipation of exhaust heat (when not fully used), must plausibly cost less than $3,000 per kW$_e$ in large production volumes (e.g., one million units). The $3,000 cost of the generator system itself includes all components needed to take pipeline natural gas and produce electricity (ac, 60 Hz) and exhaust heat as outputs; the costs of installation (labor) and balance of plants (smart meters and heat exchangers for integration with other systems) of ~$1,400 are not included. An alternator efficiency (η_{alt}) of 0.8 to 0.96 can be assumed for the purpose of FOA application if the alternator is not integral to the generator under development. The alternator cost needs to be included in the system CAPEX. The cost of commercially available alternators varies essentially linearly as the efficiency increases from 0.8 to 0.96 according to: Alternator cost [$] = 3250*$\eta_{alt}$ – 2520. Systems that do not need an alternator can exclude this cost.

1.7-1.9 Emissions for NOx, CO and VOCs should comply with CARB 2007 emissions limits for distributed power generation. Concept papers should briefly address needed strategies for limiting emissions. Full applications must provide a more complete discussion relative to the state-of-the-art numbers in a specific category of technology (e.g. ICE) and how improvements are made with respect to the baseline performance in the literature. Mitigation technologies are allowable as long as the cost is included in the system CAPEX.

1.10 For GHG emissions, only CO_2 and CH_4 are considered by the GENSETS Program. CO_2eq value for CH_4 must be evaluated using its 100 year GWP value of 28, i.e., 1 g of CH_4 corresponds to 28 g of CO_2eq. The total system-out CO_2eq must be less than 1100 lb/MW-hr.

1.13 The system must be able to operate at methane numbers as low as 70. Methane number is defined using the following equations[45]:

Motor octane number (MON) = $-406.14 + 508.04*(H/C) - 173.55*(H/C)^2 + 20.17*(H/C)^3$

Methane number (MN) = $1.624*MON - 119.1$. H/C is the fuel hydrogen to carbon ratio.

A Wobbe index[46] of 1328 ±8% is allowed to accommodate different natural gas compositions.

F. APPLICATIONS SPECIFICALLY NOT OF INTEREST

The following types of applications will be deemed nonresponsive and will not be reviewed or considered (see Section III.C.2 of the FOA):

- Applications that fall outside the technical parameters specified in Section I.E of the FOA
- Applications that were already submitted to pending ARPA-E FOAs.
- Applications that are not scientifically distinct from applications submitted to pending ARPA-E FOAs.
- Applications for basic research aimed solely at discovery and/or fundamental knowledge generation.
- Applications for large-scale demonstration projects of existing technologies.
- Applications for proposed technologies that represent incremental improvements to existing technologies.
- Applications for proposed technologies that are not based on sound scientific principles (e.g., violates a law of thermodynamics).
- Applications that do not address at least one of ARPA-E's Mission Areas (see Section I.A of the FOA).
- Applications for proposed technologies that are not transformational, as described in Section I.A of the FOA and as illustrated in Figure 1 in Section I.A of the FOA.
- Applications for proposed technologies that do not have the potential to become disruptive in nature, as described in Section I.A of the FOA. Technologies must be scalable such that they could be disruptive with sufficient technical progress (see Figure 1 in Section I.A of the FOA).
- Applications that are not scientifically distinct from existing funded activities supported elsewhere, including within the Department of Energy.
- Applications that propose the following:
  - CHP systems that employ fuel cells (ARPA-E has previously solicited for innovative fuel cell technology for distributed generation applications through its REBELS FOA)
  - Internal and external combustion systems that are powered by fuels other than natural gas, e.g., gasoline and diesel engines.
  - Employment of dual-fuel combustion such as diesel/natural gas fuel blends
  - Concepts with more than 1-kW_e power generation capacity

[45] http://www.arb.ca.gov/regact/cng-lpg/appd.pdf
[46] https://www.naesb.org//pdf2/wgq_bps100605w2.pdf